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LEVEL II

Comparison of Fog Drop Size Spectra Measured by Light Scattering and Impaction Techniques

BRUCE A. KUNKEL

10 February 1981

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METEOROLOGY DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

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FOR THE COMMANDER

John Howard

Chief Scientist

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A comparison was made between the drop size data obtained with a PMS FSSP-100 and a Calspan droplet sampler. Data were collected in simulated fogs in the Calspan environmental chamber and in natural fogs at the AFGL Weather Test Facility at Otis AFB, Massachusetts. Above 4 μm radius, the data from the two instruments agree quite well. Below 4 μm, however, the Calspan sampler shows a decrease in droplet count with decreasing radius whereas the FSSP shows an increase in count with decreasing radius. As a result, in natural fogs the Calspan sampler frequently shows a mode in the

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droplet concentration between 4 and 8 μm whereas the FSSP frequently shows no mode in droplet concentration existing within the drop size range of the instrument. In the simulated fogs, where the concentration of small particles was low, the modes agree very well. Since the droplets below 4 μm contribute little to the liquid water, there is excellent agreement in the distribution of liquid water with particle size for both simulated and natural fog. The extinction coefficients calculated from the FSSP drop size distribution are lower than the measured extinction coefficients in the lighter fogs but larger in the denser fogs.

Preface

Many thanks go to Mr. Stuart J. Sheets for installing and maintaining the forward scatter spectrometer system in both the chamber and field tests, to Mr. Donald A. Chisholm for his critical review of this report, and to Miss Karen A. Sullivan for her many typings of the report. The author also wishes to acknowledge the Calspan personnel, in particular, Messrs. Roland Pilié and Eugene Mack for their participation and cooperation in this comparative study.

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1. INTRODUCTION

As part of its effort to develop improved short-range fog prediction techniques, AFGL has an ongoing study to learn more about the structure and evolutionary processes that take place during the life cycle of a fog event. As part of this effort AFGL recently acquired two Forward Scatter Spectrometer Probes (FSSP-100) manufactured by Particle Measuring Systems Inc (PMS) of Boulder, Colorado[1] in order to measure the evolution of the droplet spectra during fogs occurring at the AFGL Weather Test Facility (WFT) at Otis AFB, Massachusetts.

In order to obtain confidence in the drop size data from the FSSP-100, it was decided that comparative measurements with another type of drop size instrument would be beneficial. The Calspan droplet sampler[2] was chosen because of its wide use in the collection of fog drop size data. More data from different locations have been collected with this instrument than with any other known drop size instrument. Data have been obtained from off the California coast from Eureka to San Diego, in

(Received for publication 6 February 1981)

1. Knollenberg, R.G. (1976) Three New Instruments for Cloud Physics Measurements: The 2-D Spectrometer, the Forward Scattering Spectrometer Probe, and the Active Scattering Aerosol Spectrometer, Preprint International Conference on Cloud Physics, Boulder, Colorado, pp 554-561.

2. Mack, E.J., Wattle, B.J., Rogers, C.W., and Pilié, R.J. (1980) Fog Characteristics at Otis AFB, Massachusetts, AFGL-TR-80-0340, AD A095358.

the North Atlantic off Nova Scotia, in the Gulf of Mexico, in valley fogs near Elmira, New York and Phillipsburg, Pennsylvania, at Travis AFB, Vandenberg AFB, Otis AFB, at Meppen, Federal Republic of Germany, and at the Seattle and Los Angeles International Airports. Another benefit of this comparative study is that it would allow one to better interpret differences in drop size data collected with the FSSP-100 in one location with Calspan droplet sampler data collected in another location.

In this study, comparative tests were conducted in a variety of simulated fogs produced in the Calspan cloud chamber during a three-day period from 4 through 6 March 1980, and in natural fog during a three-week period from 30 June through 18 July 1980 at the AFGL Weather Test Facility. The Calspan drop size data from the chamber tests are included in a Contract Interim Report.[3] The various data collected by Calspan during the Otis program are presented in a Contract Final Report.[2] This report presents a comparison of the AFGL and Calspan droplet data from these tests and attempts to explain some of the differences in the data.

2. INSTRUMENTATION

The principal instrumentation used during the comparative tests were:

(1) The PMS forward scatter spectrometer Probe (FSSP-100),

(2) A Calspan droplet sampler,

(3) A Calspan built transmissometer in the chamber tests, and

(4) An EG&G forward scatter meter in the WTF tests.

The FSSP-100 works on the principal that the magnitude of light scattered in the forward direction by a droplet is directly related to droplet size. As droplets flow through a volume illuminated by a 5-mW He-Ne laser, the scattered energy is relayed through a right-angle prism and an interference filter and collected by the scattering photodetector module (Figure 1). An aspirator, mounted on the probe, produces a flow rate of 25 m/sec through the sampling area to ensure the measurement of representative samples and a constant sample volume. There are four overlapping size ranges, with each size range divided into 15 linear size intervals. In total, up to 30 non-overlapping size bins in the 0.25 to 23.5 μm radius range are available. A data acquisition system accumulates the droplet count in the 15 size bins of a given range setting over a prescribed time period and then transfers the information to magnetic tape. The system was operated so that it sequentially stepped through the four size ranges every 25 sec, thus providing a complete spectrum from 0.25 to 23.5 μm radius.

3. Mack, E.J. (1980) Collection and Reduction of Drop Size Distribution Data in Simulated and Natural Fogs: Chamber Fog Tests, Interim Technical Reports, Contract No. F19628-80-C-0041, May 1980, pp 99.

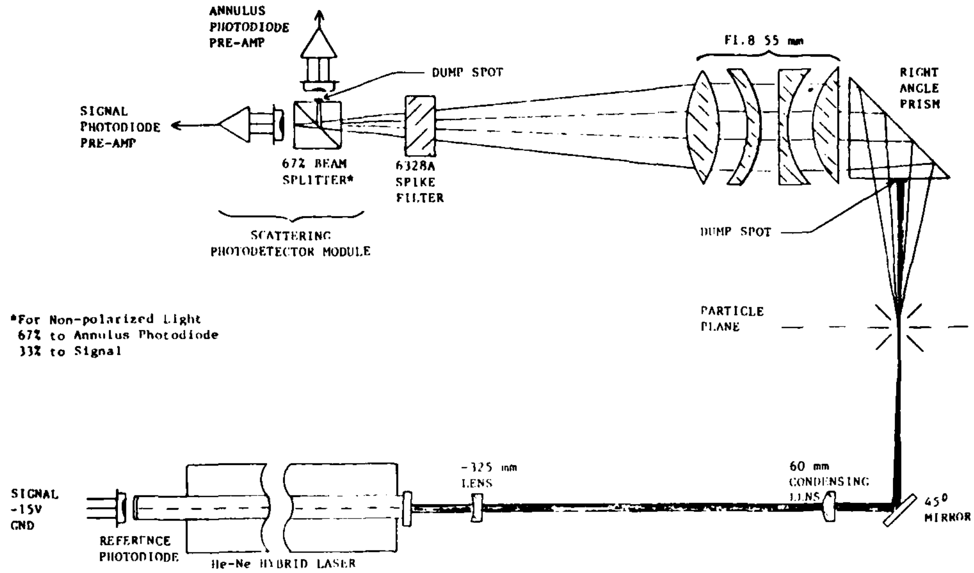


Figure 1. Optical Diagram of the FSSP-100

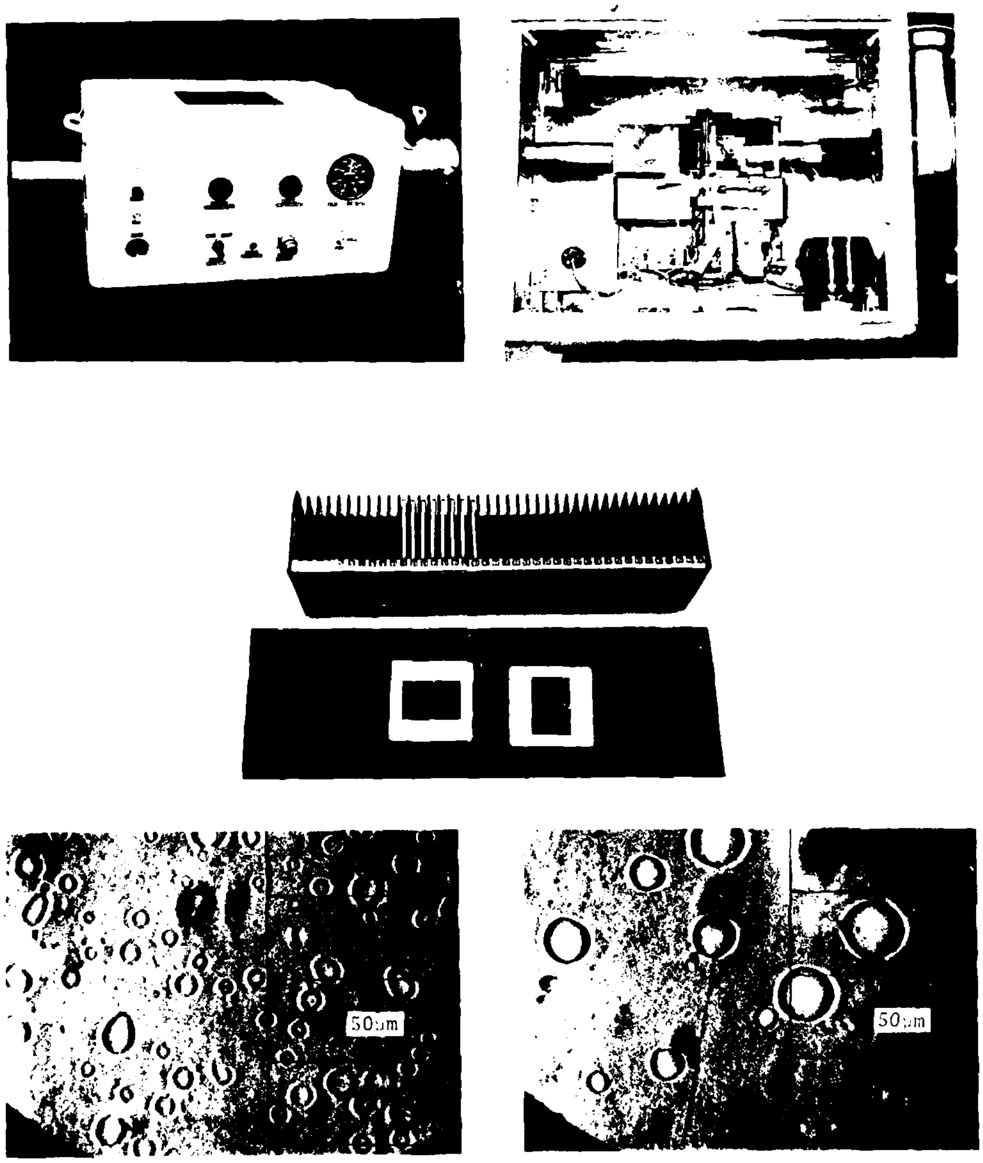
The Calspan droplet sampler, collects droplets on a glass slide coated with a thin film of gelatin, (Figure 2). The slides, which measure 4 mm in width, are injected into a high speed flow through an opening in the sampling tube. The flow rate can be varied to obtain impact velocities ranging from 20 to 80 m/sec. Slide injection is accomplished with a modified 35-mm photographic slide chamber. When the coated slide is exposed to the air flow in the tube, droplets in the air volume swept out by the slide, impinge on the gelatin coating and form a crater-like depression approximately twice the diameter of the droplet. The device operates automatically and is capable of sampling every few seconds. Slide exposure can be regulated from 0.1 sec to tens of sec depending on the fog density.

Reduction of the droplet data is performed manually from photomicrographs of the sample slides obtained with a phase contrast microscope. After adjusting for the collection efficiency, a normalized drop size distribution $n(r_i)$ is produced [$n(r_i)$ is the fraction of drops of radius r_i]. Droplet concentration (N) and liquid water content (LWC) are then computed by using the measured extinction coefficient (σ) and the expressions

$$N = \frac{\sigma}{2\pi \sum n(r_i)\, r_i^2} \qquad (1)$$

and

$$LWC = \frac{4\pi N}{3} \sum n(r_i)\, r_i^3 . \qquad (2)$$



a) Radiation Fog b) Advection Fog

Figure 2. Calspan Fog Droplet Sampler, Slide Magazine, Gelatin-Coated Sample-Slides and Droplet Replicas (Courtesy of Calspan Corp.)

The extinction coefficients were measured with a Calspan built transmissometer in the chamber tests and an EG&G forward scatter meter in the WTF tests. The Calspan-built transmissometer uses a once-folded collimated beam of white light extending across the chamber which is 9 m wide. The EG&G forward scatter meter measured light scattered from the incident ray over a 20° to 50° forward angle. The distance between the transmitter and receiver is about 1 meter.

A breadboard model of a Spectron Development Laboratories (SDL) particle sizing interferometer was also included in the chamber tests. In this instrument, the technique for sizing spherical droplets is based on the measurement of the relative phase shift that occurs when a droplet passes through two intersecting light waves from a 15-mW HeNe laser. Droplets passing through the focal volume scatter light to the collecting lens situated at some off-axis angle. The droplet size is then determined from the amplitude modulation of the interference pattern formed by the scattered light. The sample volume per unit time can be obtained by measuring the period of the modulated signal which is a function of the droplet velocity. The chief advantage of the interferometer over most drop size measuring instruments is that the sample volume is optically defined and the measured droplets remain undisturbed by the measurement procedure. Considerable difficulty was encountered with the calibration and alignment of this device. As a result, data were available in only 3 of the 12 tests. The available data indicated larger droplets and broader distributions than the FSSP-100 and Calspan droplet sampler and resulted in unrealistically high liquid water contents and extinction coefficients. Further development and testing of the SDL interferometer is necessary before it becomes a reliable instrument for measuring droplets as small as to 1-μm radius.

3. SIMULATED FOG CHAMBER TESTS

The first set of comparative tests were conducted in Calspan's Ashford environmental chamber. This facility consists of a cylindrical chamber of 9-m diameter and 9-m height. The total volume is 590 m^3, making it one of the largest environmental chambers in the United States. This is important for minimizing wall effects and closely simulating actual atmospheric conditions.

Fogs are produced by first wetting the chamber walls thoroughly with water from a rotating spray nozzle. The chamber is then pressurized to about 30 mb above ambient atmospheric pressure and the air is circulated to establish the desired equilibrium conditions. Fog formation is induced by rapidly venting the chamber air at a controlled average rate of about 3 mb/min. After fog formation occurs, fog persistence is achieved by continued slow expansion of the chamber

air to a pressure of about 30 mb below ambient. Fogs of different droplet spectra can be produced by altering the nuclei count by either filtering out nuclei or adding nuclei before producing the fog.

The FSSP-100 and the Calspan droplet sampler were placed about 1 m above the floor in the chamber. They were located 2 to 3 m from the wall and spaced sufficiently far apart so as not to interfere with each other. The transmissometer was 1.2 m above the floor.

A total of 12 tests were conducted; each test lasting for 20 minutes. The nuclei count was varied for each test. The normal procedure was to filter the chamber overnight and during lunch hour so that a low droplet concentration fog could be produced. The nuclei count was then increased for each successive test during that morning or afternoon session. Normally three or four tests were conducted per session.

The FSSP operated continuously during each test, accumulating data over the four size ranges during 25-sec time periods. This represented approximately a 75 cm^3 sample volume for each size range. The measurements were then taken with the Calspan sampler every 3 min, starting 5 min into the test. A sample normally consisted of 250 to 350 droplets. Therefore, depending on the density of droplets the sample volume ranged from 0.5 cm^3 to 40 cm^3.

Two FSSP-100s were used during the tests. However, the data from one of the probes looked suspicious. Upon examining the probe after the tests were completed, it was found that the optics were out of alignment. The data from that probe, therefore, could not be used in the comparative study. It was also discovered after the tests that the edge effect reject circuitry, which eliminates droplets near the edge of the sampling area, had been incorrectly wired at the factory and was inoperative. Without the reject circuitry, the FSSP will underestimate the size of the droplets that pass through the sampling area at the edge of the incident beam. Also, because of the increase in sampling area, the probability of two or more droplets in the sample volume at the same time is increased, thus resulting in an undercount of droplet number and an overestimation of drop size. The probability of coincidence and edge effect is only a few percent and since they tend to compensate each other the overall effect on the distribution in most cases is believed to be small. The sampling area, however, is increased by approximately 60 percent, and this was taken into account when determining the droplet concentrations, extinction coefficients and liquid water contents.

The FSSP measures droplets as small as 0.25 μm radius while the Calspan sampler is reported to measure droplets down to 1 μm radius. Since the sub-micron particles could have a significant effect on the mean size and total concentration, particles less than 1 μm, measured with the FSSP, were not included in the comparative study. The sub-micron particles were included when calculating the extinction coefficients. However, their effect was negligible.

Since some of the chamber fogs were similar, it was agreed that Calspan would reduce the drop size data from eight of the twelve tests. Each test consisted of six samples taken with the Calspan droplet sampler, thus resulting in a total of 48 samples. Figure 3 shows the comparison of the drop size distribution as measured by the FSSP-100 and the Calspan droplet sampler at the 8-min period during six of the eight tests. The FSSP distributions were accumulated over a 25-sec time period. The hatched area represents the Calspan distribution. Droplet spectra range from small droplets, narrow distribution to large droplets, broad distribution. The modes agree quite well in terms of radius and concentration. However, the FSSP-100 measured a broader distribution, picking up many droplets below 5 μm radius that the Calspan droplet sampler did not detect. Also, in the smaller droplet fogs, such as Tests 1 and 7, the FSSP-100 shows the presence of larger droplets than those detected by the Calspan sampler.

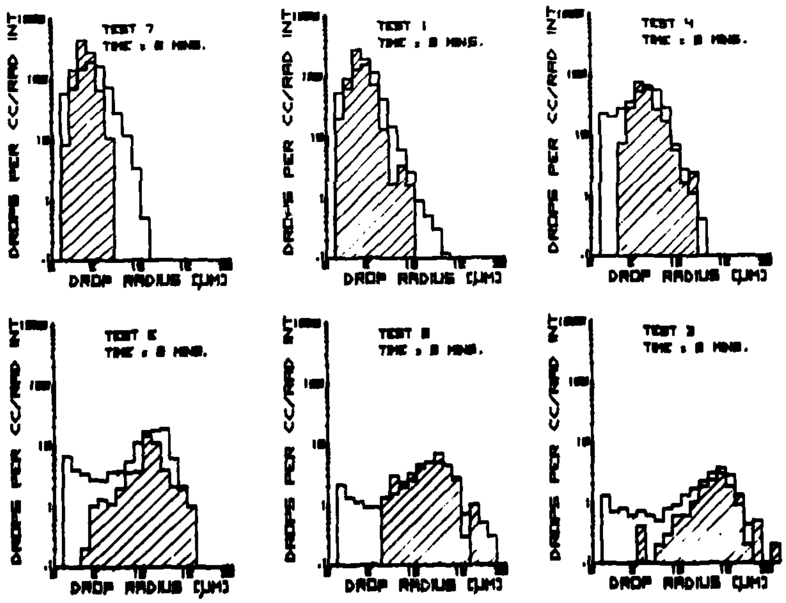


Figure 3. Six Examples of Droplet Concentration Spectra From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Samples were taken in the Calspan Environmental Chamber

Comparisons of the drop size distributions for all 48 samples are presented in Figure A1. In all cases, the FSSP-100 recorded bimodel distributions with a

minimum count somewhere between 1 and 4 μm radius. The peak concentration at the large end of the spectra represents the fog droplets that formed on active nuclei and the peak at the lower end represents the inactive nuclei.

Figure 4 shows examples of the distribution of liquid water by droplet size for the same samples shown in Figure 3. Generally, the peak in liquid water measured by the Calspan samplers occurs about 1 μm lower than that measured by the FSSP-100.

Figure 5 shows a comparison of the variation within each test of the concentration (N) and the mean linear radius (MLR) of droplets greater than 1 μm radius and the resulting liquid water contents (LWC) for the FSSP-100 and Calspan droplet sampler. Samples taken at 5, 8, 11, 14, 17 and 20 min for each of the eight tests are shown. Table 1 lists the N, MLR, mean volume radius (MVR), standard deviation (SD) and liquid water content (LWC) for the two drop-size instruments for the six time periods of the eight tests.

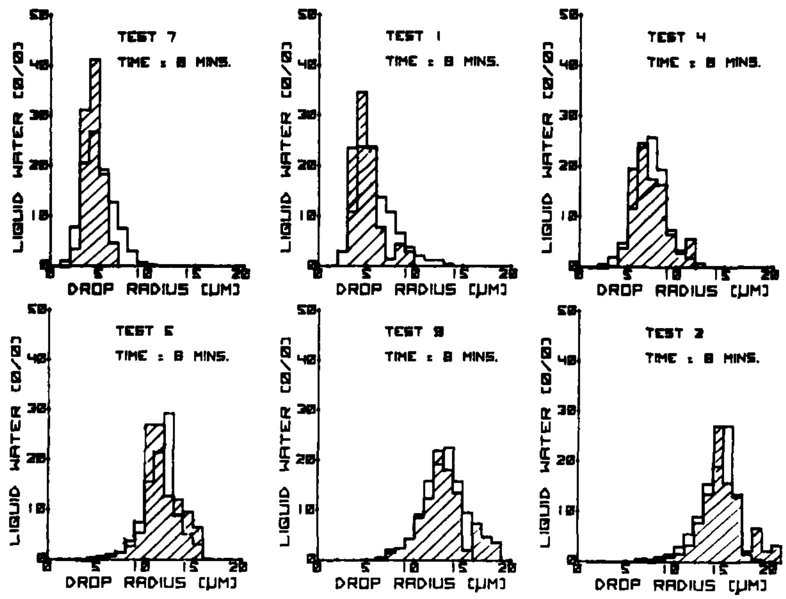


Figure 4. Liquid Water Spectra for the Same Samples Shown in Figure 3

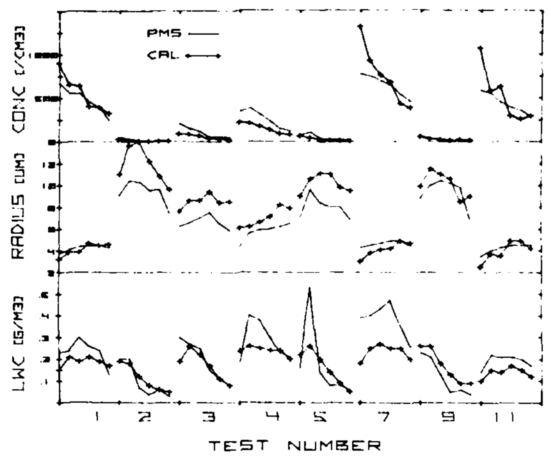


Figure 5. Time Plots of the Droplet Concentration, Mean Linear Radius and Liquid Water Content for the Eight Chamber Tests

In the small droplet fogs (Tests 1, 7, 11) the FSSP is measuring larger mean droplet sizes than the Calspan sampler because the probe is detecting droplets at the upper end of the spectrum that the sampler is not detecting. In the larger droplet fogs, the opposite is true in that the probe is detecting droplets at the lower end of the spectrum that are not detected by the sampler, thus showing a smaller mean droplet size than the sampler. Likewise, the FSSP shows lower droplet concentrations in the smaller droplet fogs and higher concentration in the larger droplet fogs than does the Calspan sampler. In all cases, the FSSP shows a broader distribution than the Calspan sampler. The computed liquid water contents from the Calspan sampler and transmissometer data are generally lower than those from the FSSP.

To further test the accuracy of the FSSP-100, the calculated extinction coefficients derived from the drop size spectra were compared with the extinction coefficients measured with the Calspan transmissometer. A scatter plot of the values from the eight tests is shown in Figure 6. Also shown is the least-square-fit for a power curve. Although the correlation appears to be excellent, the calculated extinctions exceed the measured values by about 35 percent at the higher values. Below an extinction coefficient of 27 km^{-1}, or above a visual range of 150 m, the measured extinction coefficients tend to exceed the calculated values. Figure A2 shows the calculated extinction coefficients plotted against the measured extinction coefficients for all 12 tests. The smooth curve represents the transmissometer extinction coefficient and the other curve represents 25 sec averaged extinction coefficients derived from the FSSP-100 data.

Table 1. Comparison of Microphysical Data During Eight Tests in the Calspan Cloud Chamber

		CONC (#/cm^3)		MLR (μm)		MVR (μm)		S.D. (μm)		LWC (g/m^3)	
TEST	MIN	CAL	PMS	CAL	PMS	CAL	PMS	CAL	PMS	CAL	PMS
1	5	907	645	3.2	3.8	3.4	4.4	0.8	1.5	.15	.22
	8	660	615	3.9	4.2	4.2	4.7	1.1	1.6	.21	.27
	11	645	548	3.9	4.4	4.1	5.0	0.9	1.7	.19	.29
	14	407	460	4.7	4.5	5.0	5.2	1.1	1.8	.21	.27
	17	399	379	4.5	4.5	4.8	5.3	1.2	2.0	.19	.23
	20	329	244	4.6	4.3	4.9	5.1	1.2	1.9	.17	.13
	MEAN	558	481	3.9	4.2	4.1	4.9	1.0	1.7	.18	.23
2	5	31	47	11.0	9.0	11.4	10.1	2.1	3.4	.19	.20
	8	15	28	13.6	11.1	14.1	12.6	2.8	4.4	.18	.23
	11	8.9	9.5	14.0	10.8	14.6	12.9	3.0	5.4	.12	.08
	14	8.3	6.9	12.2	10.4	13.3	12.5	3.7	5.2	.08	.06
	17	8.3	8.8	10.8	9.6	11.9	12.8	3.4	5.3	.06	.08
	20	9.2	12.6	9.6	8.6	10.7	10.8	3.2	4.3	.05	.06
	MEAN	13.4	13.8	11.8	9.8	12.4	11.4	2.8	4.2	.11	.12
3	5	94	195	7.6	6.3	7.9	7.1	1.3	2.4	.19	.29
	[illegible]	91	152	8.6	6.7	8.8	7.7	1.4	2.7	.26	.29
	11	71	116	8.6	7.3	9.1	8.4	2.1	3.0	.22	.29
	14	41	49	9.4	7.3	10.0	8.9	2.3	3.5	.17	.15
	17	35	52	8.4	6.5	9.0	8.1	2.4	3.2	.11	.12
	20	26	55	8.5	6.4	9.2	8.3	2.6	3.7	.08	.13
	MEAN	59	103	8.4	6.7	8.8	7.8	1.8	2.9	.17	.21
4	5	225	342	6.1	4.4	6.4	5.3	1.2	2.0	.24	.28
	8	216	377	6.2	5.6	6.6	6.5	1.5	2.1	.26	.37
	11	182	307	6.6	5.9	6.9	6.8	1.4	2.4	.25	.37
	14	142	226	7.1	6.0	7.4	6.9	1.4	2.4	.24	.30
	17	94	156	8.2	6.3	8.5	7.2	1.6	2.6	.24	.25
	20	85	117	7.9	6.5	8.3	7.6	1.7	2.8	.20	.21
	MEAN	157	254	6.7	5.6	7.1	6.5	1.4	2.3	.24	.30

Table 1. Comparison of Microphysical Data During Eight Tests in the Calspan Cloud Chamber (Cont)

		CONC (#/cm³)		MLR (μm)		MVR (μm)		S.D. (μm)		LWC (g/m³)	
TEST	MIN	CAL	PMS	CAL	PMS	CAL	PMS	CAL	PMS	CAL	PMS
5	5	68	82	9.0	7.3	9.2	8.2	1.2	2.8	.22	.19
	8	47	102	10.6	9.3	11.0	10.3	2.2	3.4	.26	.47
	11	30	33	11.1	8.9	11.8	10.6	2.7	4.2	.20	.16
	14	19	20	11.0	8.4	12.2	10.5	3.9	4.5	.14	.10
	17	16	20	9.8	8.0	11.0	10.0	3.7	4.1	.09	.08
	20	11	25	9.5	6.9	10.5	9.3	3.3	3.8	.05	.08
	MEAN	32	47	10.0	8.3	10.6	9.6	2.3	3.5	.16	.18
7	5	1317	789	3.0	3.1	3.2	4.7	0.8	1.5	.18	.33
	8	932	737	3.8	4.5	4.0	5.0	0.9	1.5	.25	.39
	11	768	712	4.1	4.8	4.4	5.3	1.1	1.7	.27	.44
	14	689	608	4.2	4.8	4.4	5.4	0.9	1.7	.25	.40
	17	440	534	4.9	4.9	5.1	5.5	1.1	1.8	.25	.37
	20	392	437	4.7	4.5	4.9	5.2	1.1	1.7	.20	.25
	MEAN	756	636	3.9	4.6	4.1	5.2	0.9	1.6	.23	.36
9	5	59	57	9.9	9.0	10.1	10.0	1.5	3.3	.26	.24
	8	36	35	11.5	10.2	12.1	11.7	2.6	4.1	.26	.23
	11	29	15	11.0	10.0	11.5	11.8	2.3	4.8	.18	.10
	14	21	9	10.6	9.9	11.5	11.7	3.1	4.7	.13	.06
	17	29	12	8.5	9.2	9.1	11.5	2.3	4.7	.09	.07
	20	24	15	9.0	7.4	9.8	10.4	2.6	4.1	.09	.07
	MEAN	33	24	10.1	9.3	10.6	10.9	2.2	3.9	.17	.13
11	5	1070	574	2.5	3.5	2.8	3.9	0.9	1.2	.10	.14
	8	585	552	3.7	4.0	3.9	4.5	0.9	1.5	.15	.22
	11	630	462	3.5	4.3	3.8	5.9	1.0	1.6	.14	.23
	14	299	409	4.9	4.5	5.2	5.1	1.2	1.7	.17	.23
	17	263	350	4.9	4.5	5.1	5.2	1.2	1.8	.15	.21
	20	299	268	4.2	4.4	4.5	5.2	1.3	1.9	.12	.15
	MEAN	524	436	3.5	4.1	3.8	4.9	1.0	1.6	.14	.20

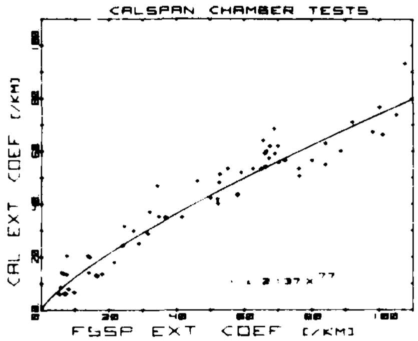


Figure 6. Comparison of the Calculated Extinction Coefficients From the FSSP-100 With the Corresponding Measured Extinction Coefficients From the Calspan Transmissometer

4. NATURAL FOG WTF TESTS

After the chamber tests, but before the WTF tests, both FSSP-100's were inspected by the manufacturer. Except for the edge effect reject circuitry and the misalignment of the one probe, the probes were in good operating order. Both problems were corrected.

To determine how well the two FSSP-100s compared with each other, a comparative test was conducted before the 3-week field program. The two probes were installed at the WTF and placed near each other. Data were collected during an 8-hr fog on the nights of 26 and 27 June 1980. Probe 1, which was used in the comparative study, was located 3.7 m above the ground and Probe 2, which was later placed at the 30-m level, was located 2.7 m above the ground. A tabulation of the data averaged over a 5-min period every half hour is presented in Table 2. The data include all droplets greater than 0.25 μm radius. There is excellent agreement in the data from the two probes. The only consistent difference is a 15 percent concentration from Probe 1. However, the higher count could be partially due to its higher position. Comparative tests between the two probes conducted in radiation fog at Hanscom AFB in September 1980 in which the two probes were placed side by side, showed only a 5 percent higher concentration from Probe 1.

Six fog episodes occurred during the three-week test period at Otis AFB resulting in about 40 hr of fog. All of the fogs were of the advection type with winds generally ranging up to 5 m/sec. Data were collected by the FSSP-100, the Calspan sampler, and other sensors during four of the six episodes.

The FSSP-100 used in the comparative study was installed at the 5-m level. The other FSSP-100 was installed at the 30-m level. Both probes were installed on the upwind side of a 60-m tower. The probes were installed on swivel mounts which allowed them to continuously face into the wind (Figure 7). Earlier tests at the WTF showed that the probes must face into the wind in order to obtain accurate counts of droplets greater than about 8 μm radius.

Table 2. Comparison of Fog Microphysical Data During Fog of 26-27 June 1980 at Otis AFB

Time (EDT)	CONC (#/cm^3) PMS1	CONC (#/cm^3) PMS2	MLR (μm) PMS1	MLR (μm) PMS2	MVR (μm) PMS1	MVR (μm) PMS2	S.D. (μm) PMS1	S.D. (μm) PMS2	LWC (g/m^3) PMS1	LWC (g/m^3) PMS2	EXCO (km^{-1}) PMS1	EXCO (km^{-1}) PMS2
2300	240	204	1.3	1.3	4.5	4.5	2.5	2.5	.094	.081	12.0	10.2
2330	228	193	1.3	1.3	4.9	4.9	2.8	2.7	.114	.095	13.2	10.8
0000	231	198	2.0	2.0	5.8	5.8	3.5	3.5	.184	.163	23.0	19.7
0030	214	185	2.1	1.8	6.2	5.9	3.8	3.5	.219	.159	25.4	18.4
0100	219	190	2.4	2.2	6.5	6.5	4.0	4.0	.257	.221	30.0	25.0
0130	213	189	2.6	2.5	7.2	7.3	4.5	4.5	.329	.298	36.5	31.8
0200	202	172	3.3	3.1	7.8	7.7	5.0	4.9	.400	.332	45.4	36.9
0230	228	196	2.7	2.5	7.1	7.1	4.4	4.4	.343	.293	38.4	31.8
0300	221	186	2.6	2.6	7.0	7.2	4.3	4.4	.322	.296	35.5	31.2
0330	200	180	2.8	2.8	7.5	7.8	4.7	4.8	.364	.355	37.7	35.7
0400	199	175	3.2	3.2	7.7	7.9	4.8	4.9	.375	.354	41.3	37.9
0430	193	173	2.7	2.7	7.4	7.6	4.6	4.7	.333	.320	34.8	32.4
0500	184	165	3.4	3.3	7.5	7.6	4.7	4.8	.335	.312	39.4	35.4
0530	185	171	3.7	3.7	7.9	8.0	4.9	5.0	.380	.358	43.4	40.3
0600	173	148	4.0	3.8	7.4	7.5	4.5	4.6	.302	.264	39.6	33.4
0630	171	147	2.4	2.4	6.3	6.4	3.8	3.9	.183	.162	22.1	19.6
0700	153	128	1.3	1.2	4.8	4.5	2.6	2.5	.071	.049	7.9	6.0
Mean	203	176	2.6	2.[illegible]	6.7	6.6	4.1	4.1	.271	.242	30.9	26.9

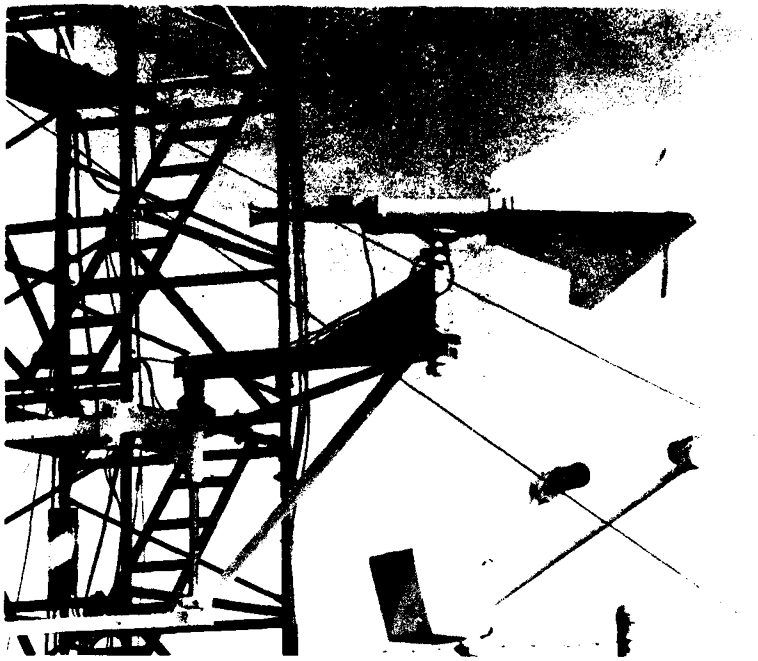


Figure 7. FSSP-100 on Swivel Mount and the EG&G Forward Scatter Meter Located at the 5-m Level of the 60-m Tower

The Calspan sampler was installed at the 5-m level and was turned into the wind when taking a sample. Samples were taken in the four fog episodes at approximately 20-min intervals for a total of 88 samples. Of the 88 samples, 33 were later reduced and included in this comparative study.

Extinction coefficient data were obtained from an EG&G forward scatter meter installed at the 5-m level (Figure 7). These data were used by Calspan to determine the droplet concentrations and liquid water contents. An additional forward scatter meter was installed at the 30-m level, and both meters provided a means for comparing the calculated extinction coefficients from the FSSP-100 data with the measured extinction coefficients.

Figure 8 shows a comparison of the drop size distributions obtained during the most dense periods of the four fogs. Again, the hatched area represents the Calspan drop size distribution. The FSSP-100 data are averaged over a 5-min period. The exposure times for the Calspan sampler are typically ~0.2 seconds. As in the chamber tests, there is good agreement in the data from the two instruments except below 4 μm radius where the FSSP-100 shows increasing concentrations with

smaller droplets. Above 4 μm, however, the number concentrations and slope of the distributions agree reasonably well. The drop concentration histograms for all 33 samples are presented in Figure A3. Figure 9 depicts the liquid water distribution for the four samples shown in Figure 8. Again, the agreement is quite good, although, there is some fluctuations in the Calspan distribution probably due to an insufficient number of droplets.

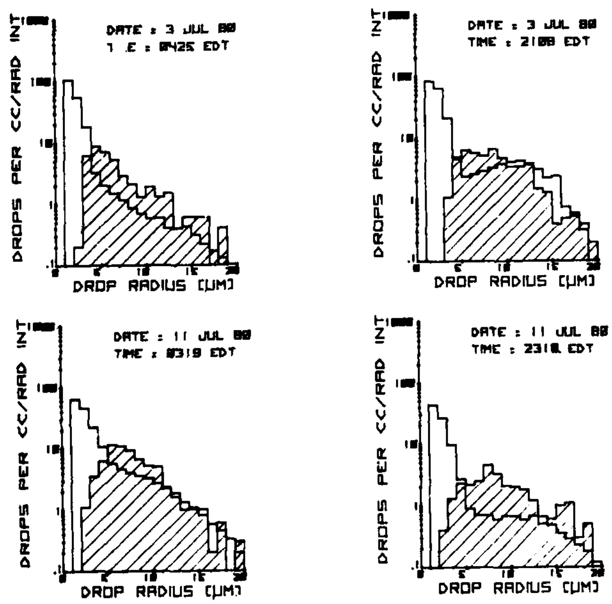


Figure 8. Four Examples of Droplet Concentration Spectra From the Calspan Sampler (hatched area) and the FSSP-100. Samples were taken at time of minimum visibility during each of four fogs at Otis AFB

A comparison of the drop size data from the Calspan sampler and the FSSP are shown in Table 3. As with the chamber tests, all droplets less than 1 μm radius have been excluded from the FSSP-100 data to provide a more representative comparison. The larger concentration of smaller droplets (< 4 μm) detected by the FSSP have a large impact on the total concentrations and the mean linear radius (MLR) and mean volume radius (MVR). The mean radii of the droplets determined from the FSSP-100 drop size distributions are considerably lower than the Calspan mean radii. Although the FSSP generally shows a broader range of droplets, the

standard deviations (SD) are not affected appreciably because of the more peaked distributions. The liquid water contents determined from the FSSP distributions are very close to those derived from the Calspan normalized drop size data and the EG&G extinction coefficient data.

The extinction coefficients derived from the 5-m and 30-m FSSP data were compared with those measured with the EG&G forward scatter meter at the same heights. Figure 10 shows a scatter plot of the two sets of values. Since the advection fogs were always denser at the 30-m level, the higher extinction coefficients generally were from the 30-m probe. The least-square-fit for a power curve is similar to that obtained in the chamber tests (Figure 6) but shows a slightly greater difference in calculated vs measured extinction coefficients. The scatter plots and least-square-fit for each of the four cases for both levels are presented in Figure A4.

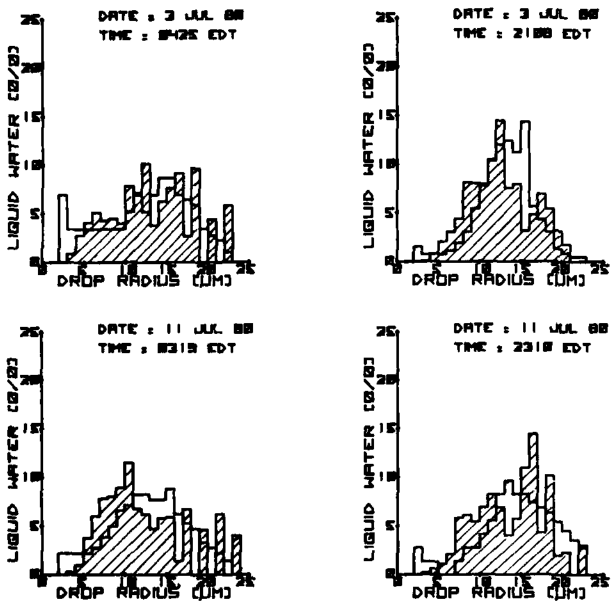


Figure 9. Liquid Water Spectra for the Same Samples Shown in Figure 8

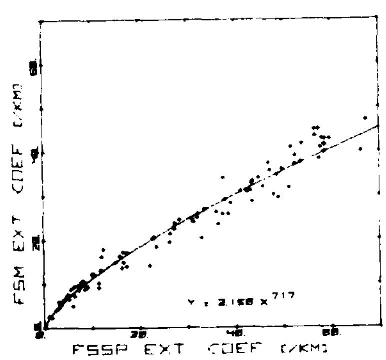


Figure 10. Comparison of the Calculated Extinction Coefficients From the FSSP-100 With the Corresponding Measured Extinction Coefficients From the EG&G Forward Scatter Meter

Table 3. Comparison of Fog Microphysical Data During Four Fogs at Otis AFB

Time (EDT)	CONC (#/cm^3) CAL	CONC (#/cm^3) PMS	MLR (μm) CAL	MLR (μm) PMS	MVR (μm) CAL	MVR (μm) PMS	S.D. (μm) CAL	S.D. (μm) PMS	LWC (g/m^3) CAL	LWC (g/m^3) PMS
3 July 1980										
0342	29	59	6.7	2.2	8.0	5.3	3.0	2.6	.06	.04
0425	41	154	7.0	2.4	8.8	4.6	3.6	2.2	.12	.06
0526	31	229	8.1	2.8	9.5	5.1	3.6	2.5	.11	.12
MEAN	34	147	7.3	2.6	8.8	5.0	3.4	2.4	.10	.07
3-4 July 1980										
2108	50	155	8.8	4.2	10.0	7.6	3.4	4.2	.21	.28
2200	14	20	7.9	2.8	8.8	6.0	2.7	3.3	.04	.02
2221	17	47	7.0	2.2	8.5	4.5	3.4	2.1	.04	.02
2329	36	142	6.8	2.8	7.7	4.8	2.5	2.4	.07	.06
0051	48	132	6.1	3.1	6.9	5.3	2.2	2.7	.07	.08
0150	39	137	7.3	3.3	8.4	5.6	2.9	3.0	.10	.10
0331	50	147	7.3	3.6	8.8	6.2	3.5	3.3	.14	.15
0455	45	222	7.9	3.2	9.0	5.1	3.0	2.5	.14	.12
MEAN	37	125	7.4	3.3	8.5	5.7	3.0	3.0	.10	.10
10-11 July 1980										
2040	13	25	5.3	2.6	7.5	6.0	3.5	2.9	.02	.02
2145	27	76	5.4	3.3	7.5	6.5	3.6	3.5	.05	.09
2207	33	52	6.9	3.4	9.5	7.0	4.5	3.8	.12	.08
2234	71	114	4.8	3.1	6.8	6.3	3.2	3.4	.09	.12
2306	42	96	7.2	2.5	9.0	5.0	3.6	2.5	.13	.05
0004	28	61	8.2	2.3	9.6	5.0	3.4	2.9	.11	.03
0052	15	15	9.3	4.9	10.8	9.0	3.8	5.0	.08	.05
0142	7	3	9.6	3.5	11.1	9.4	3.8	4.6	.04	.01
0254	44	162	7.7	4.0	8.3	6.3	3.2	3.2	.13	.17
0319	68	168	7.7	3.8	9.1	6.8	3.2	3.5	.21	.22
0402	22	43	7.9	2.9	9.1	6.4	3.1	3.2	.07	.05
MEAN	34	74	6.9	3.3	8.6	6.3	3.5	3.3	.10	.08
11-12 July 1980										
2028	7	5	7.1	2.7	8.3	8.4	3.0	3.5	.02	.01
2223	53	91	5.7	3.3	7.1	7.0	2.9	3.6	.08	.13
2310	28	95	9.0	2.9	10.6	6.7	3.9	3.3	.14	.12
2321	32	187	5.7	2.6	8.3	5.6	4.0	2.4	.08	.14
2336	39	139	6.8	2.8	8.6	6.0	3.7	2.8	.10	.12
0005	21	56	9.2	3.4	10.4	7.9	3.4	4.1	.10	.12
0019	17	35	7.8	2.7	9.1	6.8	3.2	3.4	.05	.05
0116	28	107	8.6	3.1	10.1	6.4	3.6	3.3	.12	.12
0218	43	172	7.3	2.9	9.1	5.2	3.6	2.5	.13	.10
0317	66	236	7.1	3.2	8.5	5.6	3.2	2.7	.17	.18
0407	33	207	8.0	2.7	9.1	4.3	3.1	1.9	.11	.07
MEAN	33	121	7.3	2.9	8.8	5.8	3.4	2.8	.10	.11

5. SUMMARY AND CONCLUSIONS

Simultaneous drop size measurements were made with the PMS FSSP-100 and the Calspan droplet sampler. A total of 48 samples in fogs produced in the Calspan cloud chamber and 33 samples in natural fogs at the AFGL Weather Test Facility at Otis AFB were evaluated. Measurements of the extinction coefficient were made with a Calspan built transmissometer in the chamber and an EG&G forward scatter meter at Otis AFB.

The chamber tests offered an opportunity to obtain measurements on a wide range of microphysical conditions. In the 12 tests that were conducted, the mean drop sizes and the standard deviations of the drop size distributions varied by a factor of 3 and the concentrations varied by a factor of 50. By contrast, the four fogs in which comparative data were taken at Otis AFB had relatively uniform microphysical characteristics.

The Calspan data show that the number concentrations and mean sizes of droplets in the natural fogs were within the range observed in the simulated fogs but that the distributions were broader in the natural fogs than in any of the simulated fogs. The FSSP-100 data, however, show that the number concentrations and standard deviations of the drop size distributions were within the range observed in the simulated fogs but the mean sizes were smaller than those observed in the chamber. The reason for this discrepancy is that the FSSP-100 probe indicated the presence of a large number of small droplets ($< 4\ \mu m$ radius) in the natural fogs that were not detected by the Calspan sampler. This was also true in the chamber tests but the number of small droplets created in the chamber and detected by the FSSP-100 was considerably less than occurred in the natural fogs. Droplet counts in natural fogs of up to $120/cm^3$ in the 1- to 2-μm range were measured by the FSSP-100 while no droplets were detected by the Calspan sampler in this range. Maximum counts of about $60/cm^3$ in this size range were detected by the FSSP-100 in the chamber tests. The Calspan sampler detected droplets in the 1- to 2-μm range in 25 percent of the samples, and in all cases, except one, the count was lower than the FSSP-100.

In general, the Calspan sampler shows lower concentrations of small droplets ($< 4\ \mu m$ radius) than the FSSP. This agrees with the work of Garland[4] in which he compared the differences in count using the phase contrast technique, which was used in this study, and the interference contrast technique. Much larger counts of small droplets were detected using the interference contrast technique. He concluded that the number concentration of droplets less than 4 μm radius was underestimated when using the phase contrast technique.

4. Garland, J. A. (1971) Some fog droplets size distributions obtained by an impaction method, Quart. J. Roy. Meteorol. Soc. **97**:483-494.

Above 4 μm, the shape of the distribution obtained from the two instruments agrees quite well. The main exception is in the high droplet density chamber fogs (Test 1, 7, 11) where the Calspan data do not show the larger droplets detected by the FSSP-100. The reason for this discrepancy is not clear. It is conceivable that in these higher density fogs that some multiple droplets are occupying the FSSP sample volume at the same time. The scattered energy from two or more droplets may be interpreted as a single larger droplet. This may also explain the lower concentration measured by the FSSP. In the natural fogs where the droplet densities were lower no discrepancy at the upper end of the spectrum was evident.

In the chamber tests, the modal radii agree very well as do the concentrations at the mode. However, in the natural fog cases, the Calspan sampler data would lead one to believe that a mode exists in the 4- to 6-μm range. However, the FSSP-100 data show an increasing concentration toward the smaller droplets with the highest concentration normally occurring in the 0.25- to 0.50-μm range. In the Otis fogs, a clearly defined mode occurring within the range of the FSSP-100 (0.25 - 23 μm radius) is the exception rather than the rule. A typical distribution is characterized by a sharp decrease in concentrations from 0.25 μm to about 5 μm and then a leveling off in concentration to about 15 to 20 μm and then a more rapid decrease to zero. Only occasionally does the plateau in the 5- to 15-μm range develop a mode. Measurements with the same instrument in radiation fogs at Hanscom AFB, however, reveal sharply defined modes frequently occurring within the plateau.

Comparisons were made between the extinction coefficients measured with the EG&G forward scatter meter at the WTF and the Calspan transmissometers in the chamber and those determined from the FSSP drop size distributions. Up to an extinction coefficient of about 21/km (15/km in natural fogs, 27/km in simulated fogs) the calculated extinctions are slightly lower than the measured. Above 21/km the calculated extinctions exceed the measured by as much as 55 percent in the natural fogs and 35 percent in the simulated fogs. In the lighter fogs, a greater percentage of the extinction is probably due to particles below the size range covered by the FSSP, which might explain the lower calculated values. The larger calculated extinctions in the denser fogs are difficult to explain. The fact that the calculated extinction coefficients exceed those measured by both the forward scatter meter and the transmissometer suggests that the error is in the FSSP which may be overestimating either the concentration or the droplet size in the denser fogs.

As a further check on the accuracy of the FSSP-100 used in the comparative study, its output was compared with the output from another FSSP-100 during fogs at Otis and Hanscom AFB. The agreement between the two sets of data was extremely good.

In conclusion, a great deal of confidence has been obtained in the use of FSSP-100 in accurately defining the fog drop size spectra. Although some discrepancies do exist, especially between the measured and observed extinction coefficients, the FSSP-100 can be a valuable tool in learning more about the microphysical properties and processes that take place throughout the fog life cycle. Additional measurements with the FSSP will be made at the AFGL Weather Test Facility at Otis AFB in order to expand our data base. These data, along with other types of data, will be used to develop a descriptive model(s) of the fog life cycle; the first step toward the ultimate goal of developing a reliable fog prediction model.

Appendix A

Microphysical Data

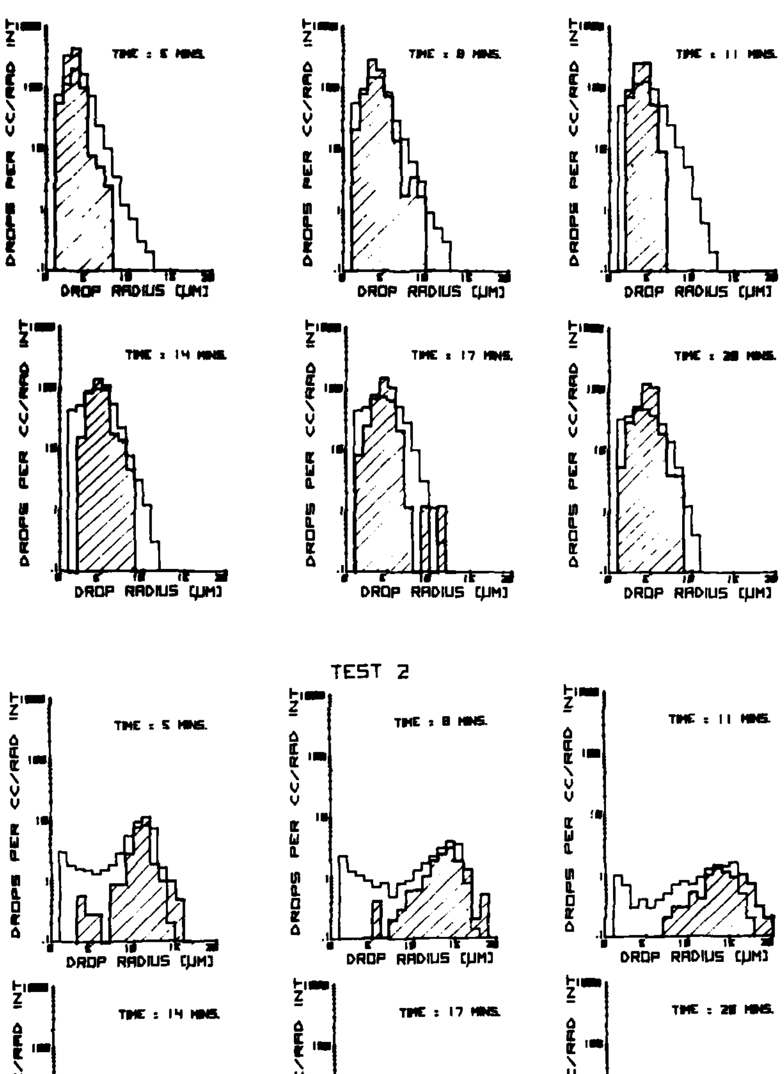


Figure A1. Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data included 6 samples from 8 simulated fogs in the Calspan environmental chamber

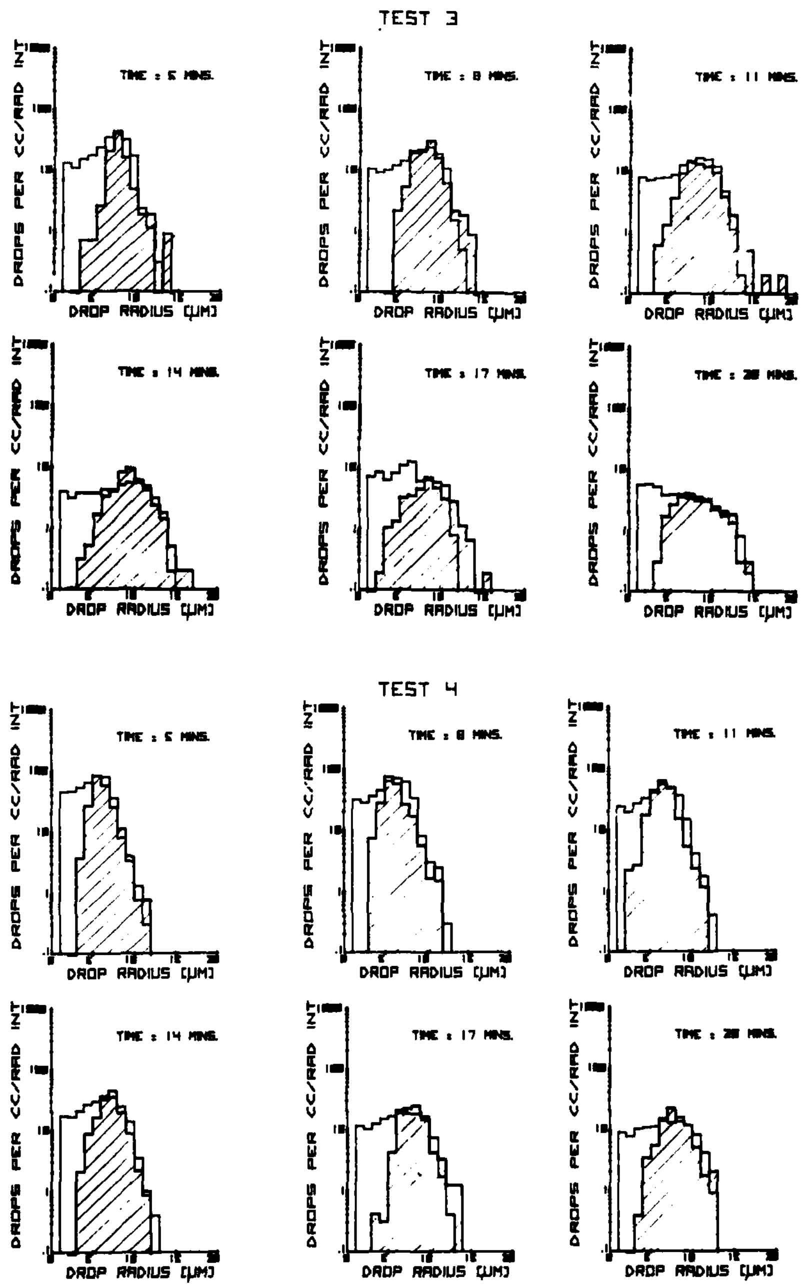


Figure A1 (Cont). Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data included 6 samples from 8 simulated fogs in the Calspan environmental chamber

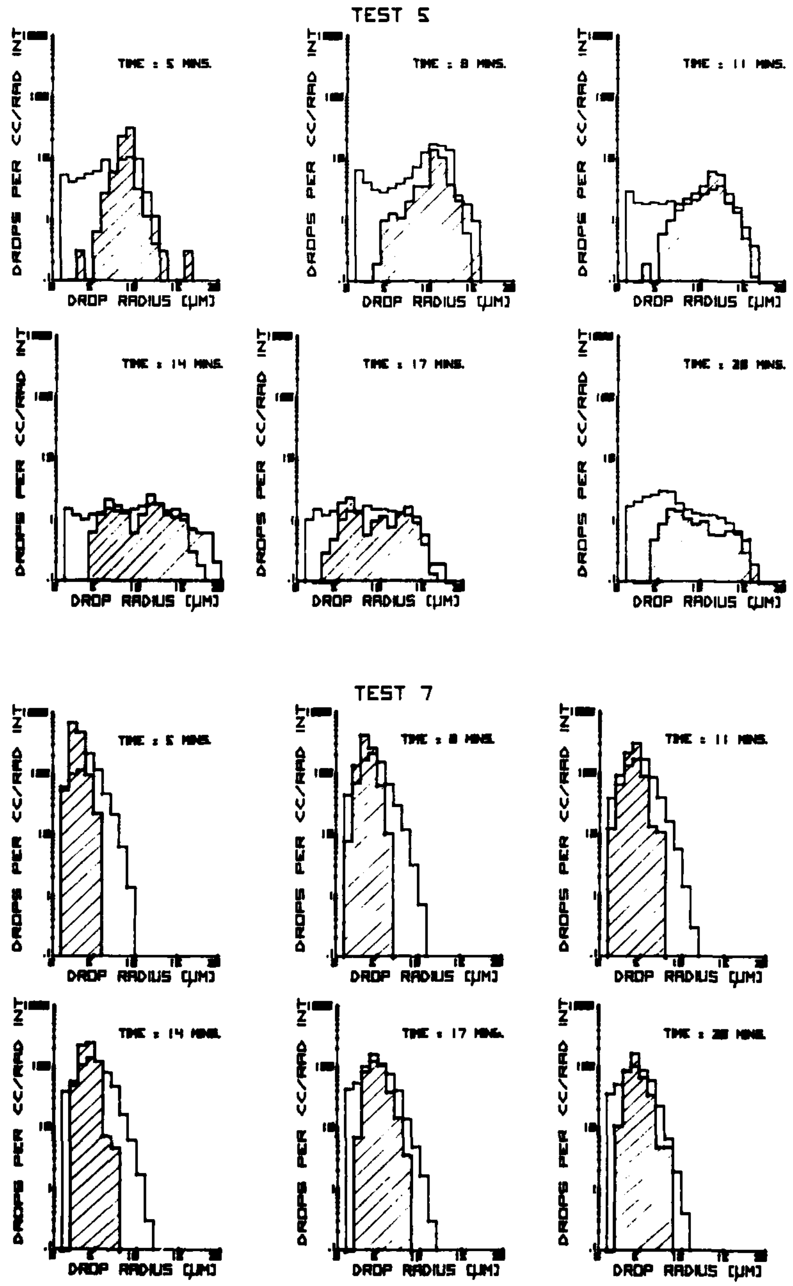


Figure A1 (Cont). Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data included 6 samples from 8 simulated fogs in the Calspan environmental chamber

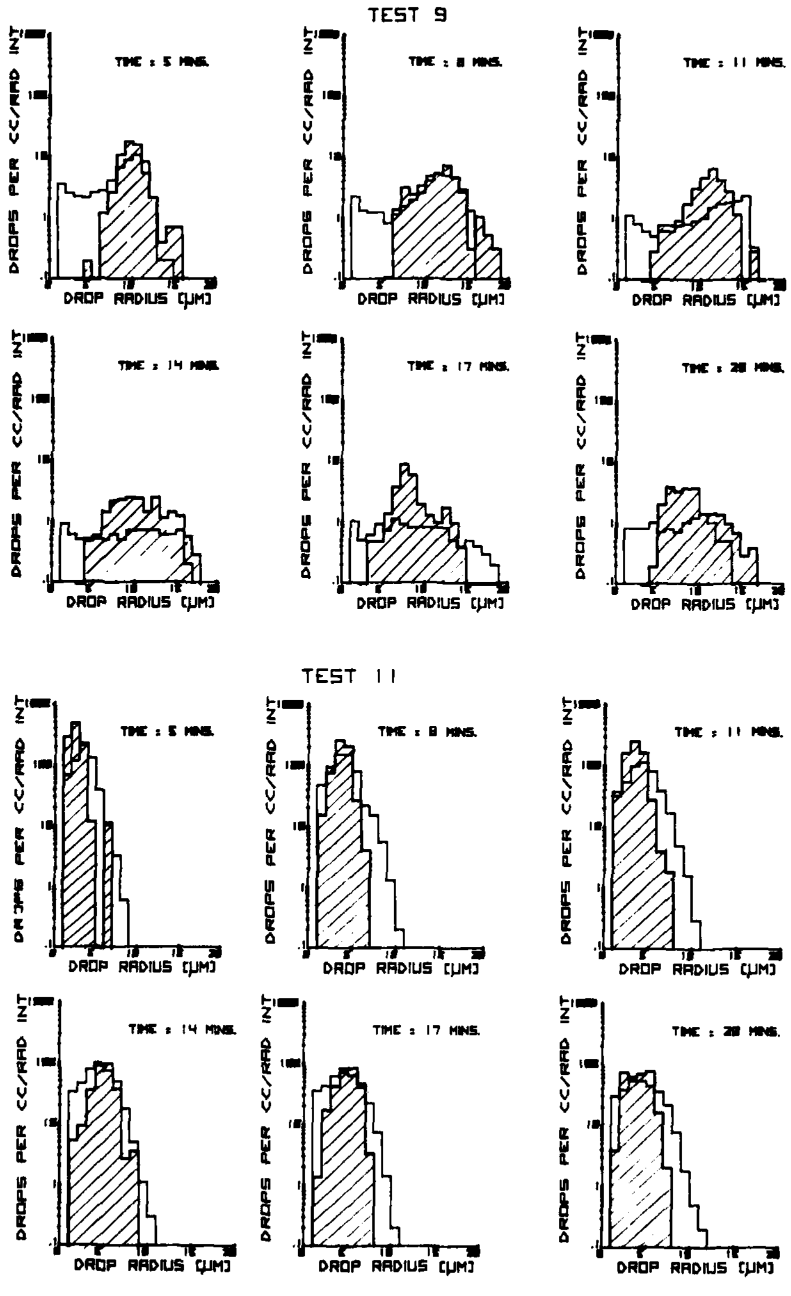


Figure A1 (Cont). Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data included 6 samples from 8 simulated fogs in the Calspan environmental chamber

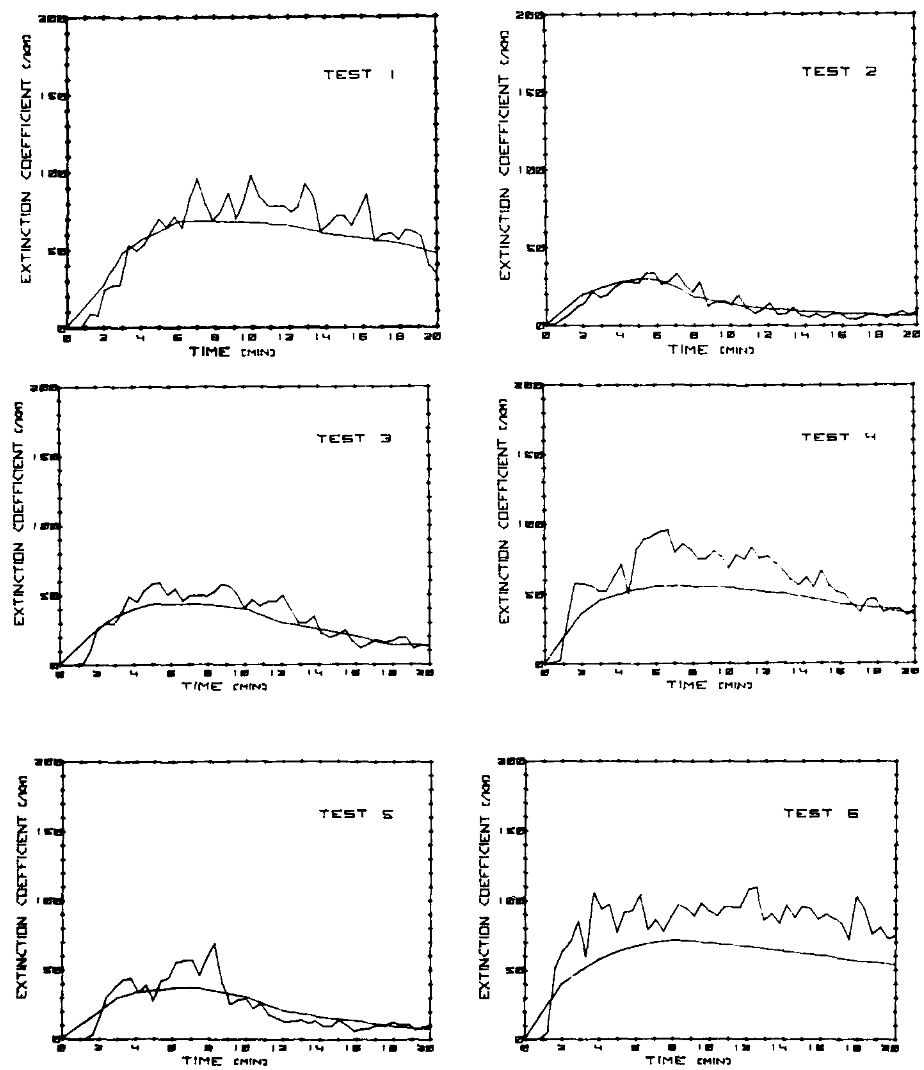


Figure A2. Comparison of the Calculated Extinction Coefficients From the FSSP-100 Drop Size Data With the Measured Extinction Coefficients (smooth curve) From the Calspan Transmissometer for the 12 Chamber Tests

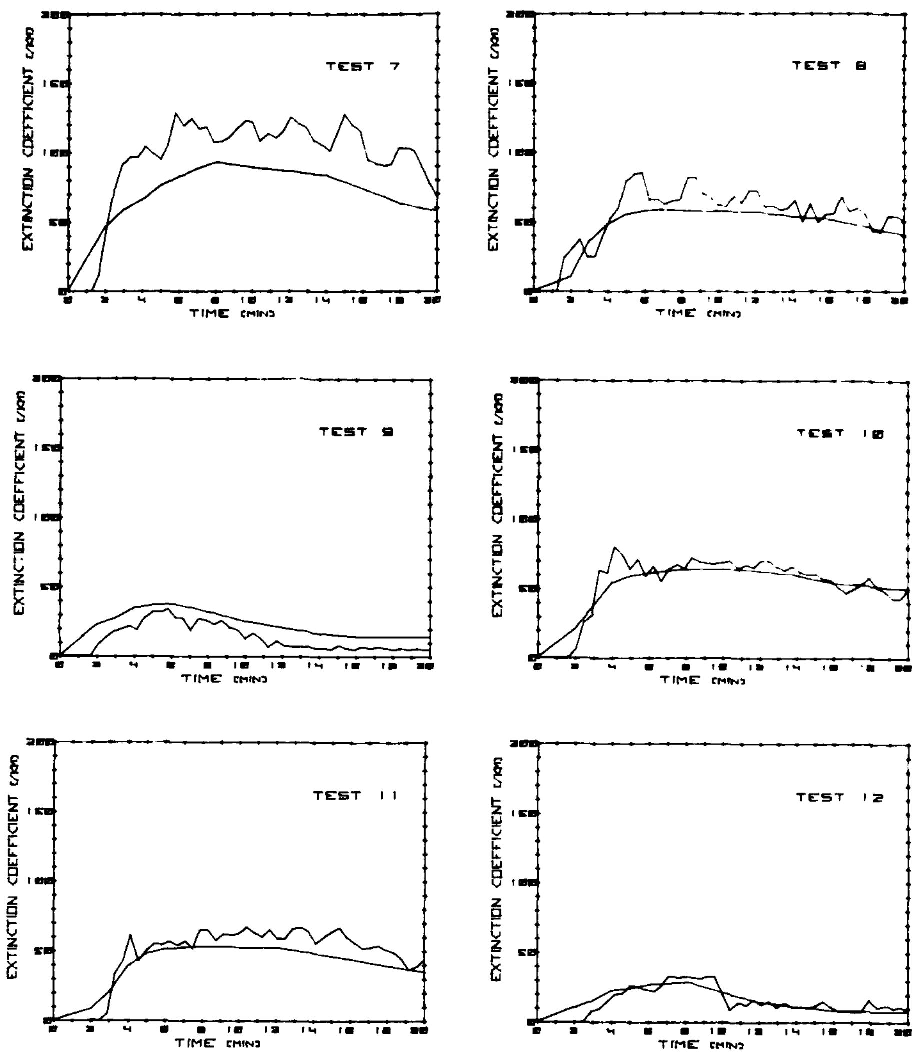


Figure A2 (Cont). Comparison of the Calculated Extinction Coefficients From the FSSP-100 Drop Size Data With the Measured Extinction Coefficients (smooth curve) From the Calspan Transmissometer for the 12 Chamber Tests

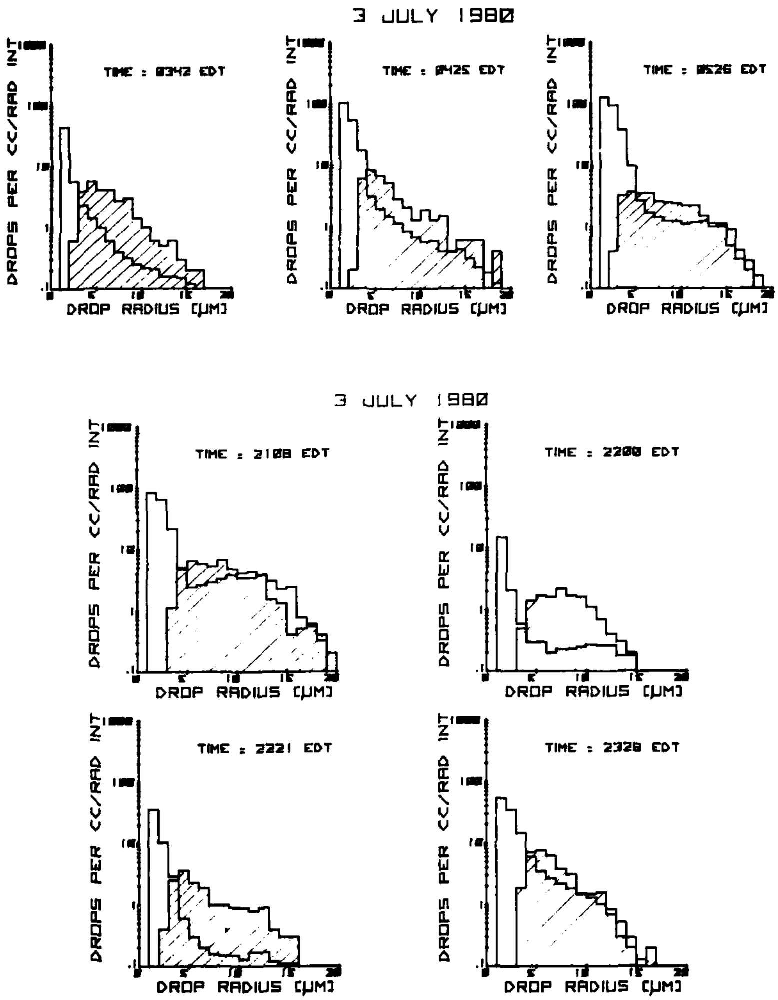


Figure A3. Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data include 32 samples from 4 fog cases at Otis AFB

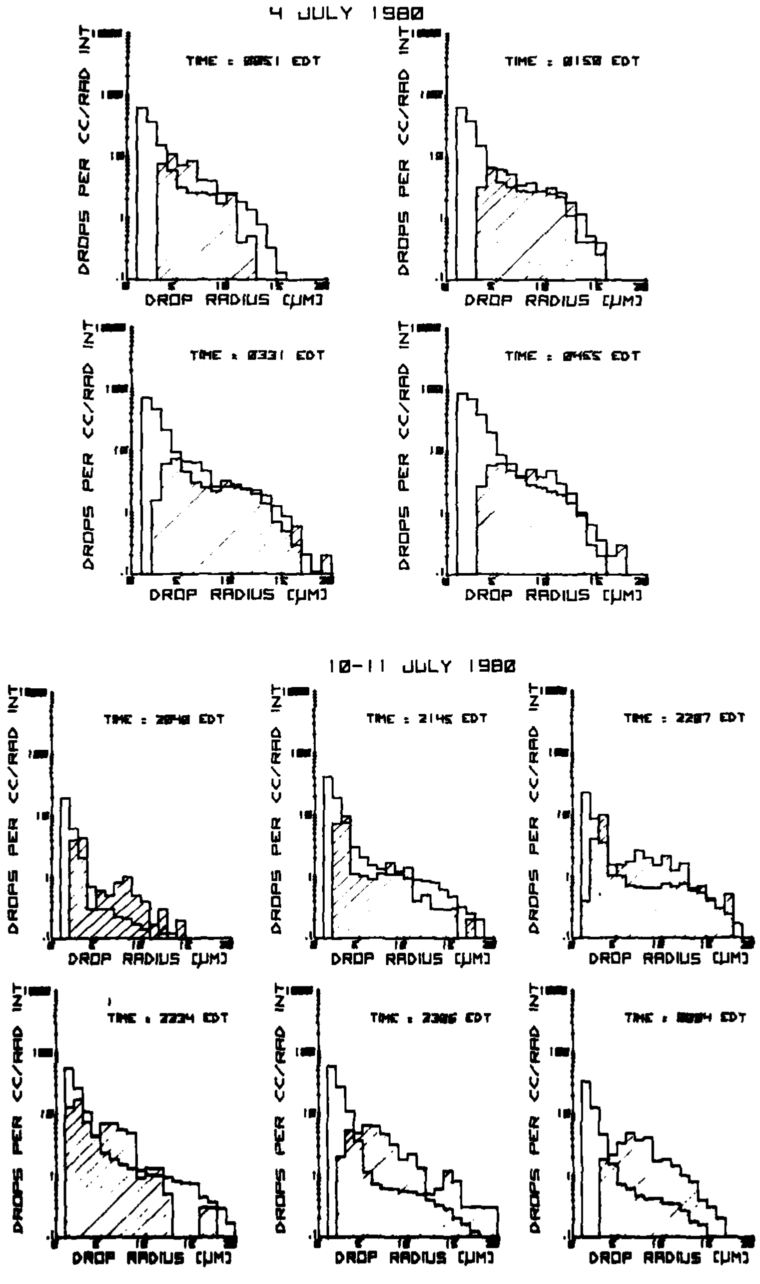


Figure A3 (Cont). Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data include 32 samples from 4 fog cases at Otis AFB

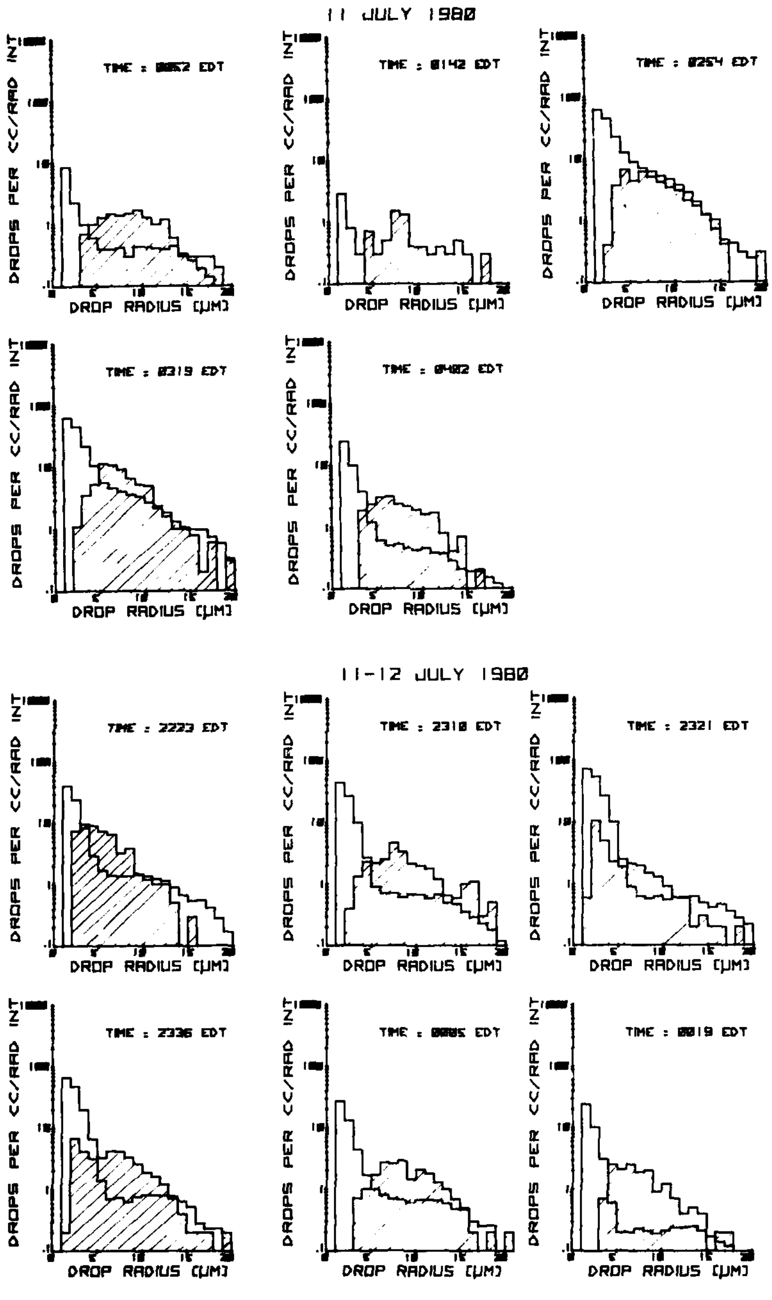


Figure A3 (Cont). Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data include 32 samples from 4 fog cases at Otis AFB

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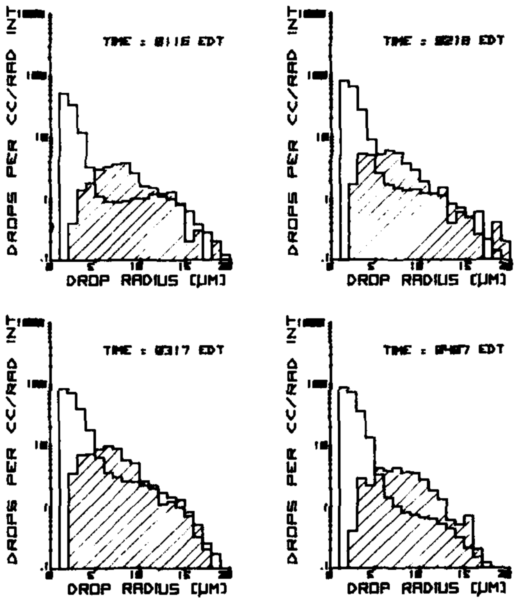

Figure A3 (Cont). Sequence of Droplet Concentration Spectra Data From the Calspan Droplet Sampler (hatched area) and the FSSP-100. Data include 32 samples from 4 fog cases at Otis AFB

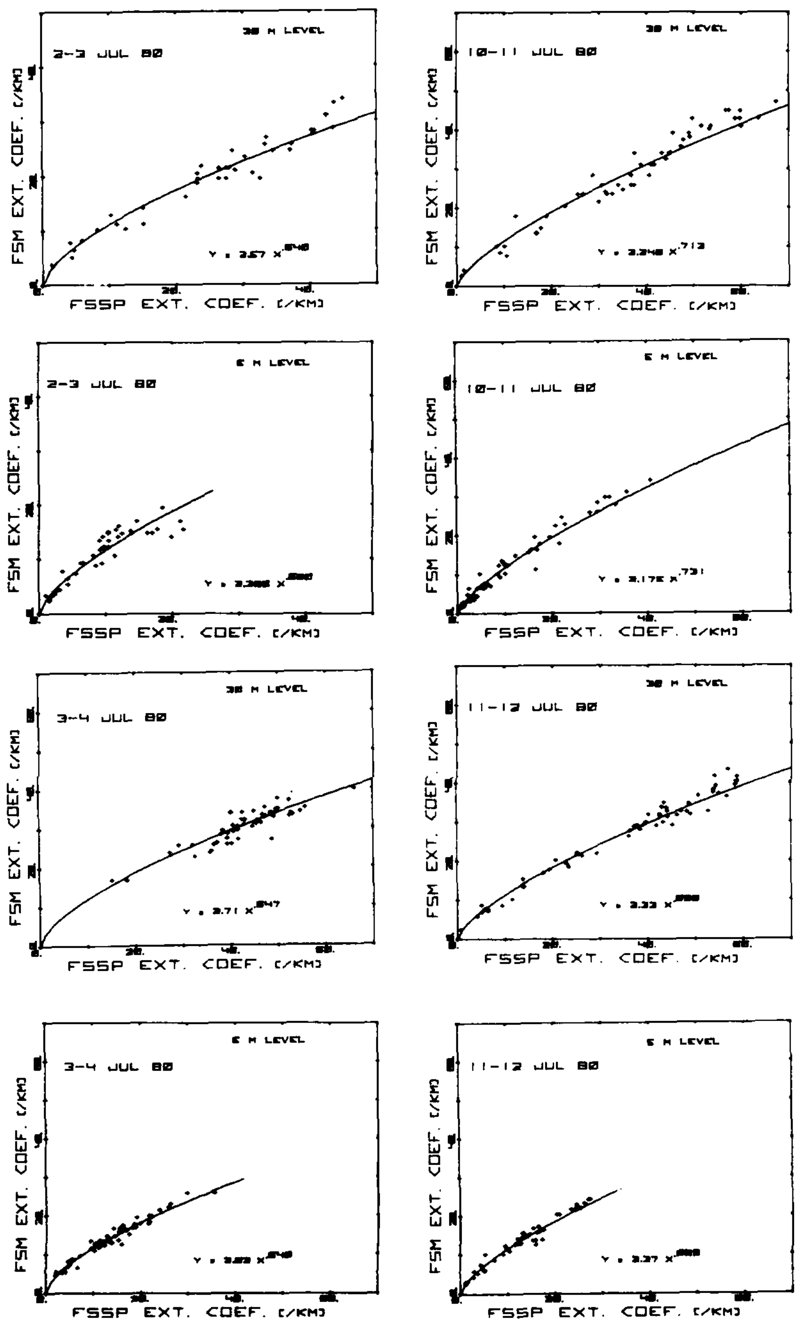

Figure A4. Comparison of the Calculated Extinction Coefficients From the FSSP-100 With the Measured Extinction Coefficients From the EG&G Forward Scatter Meter